Technology Advancement for Active Remote Sensing of Carbon Dioxide from Space using the ASCENDS CarbonHawk Experiment Simulator (ACES): First Results

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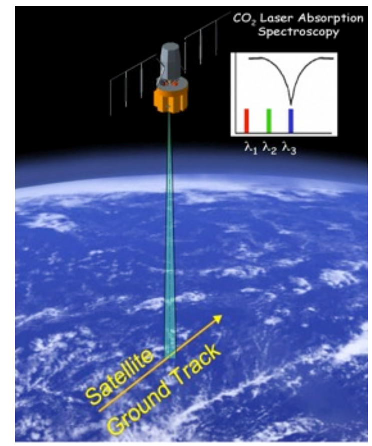

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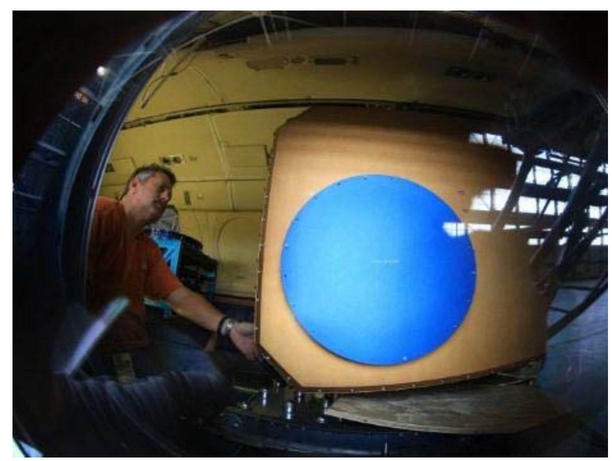


ACES Scientific Motivation

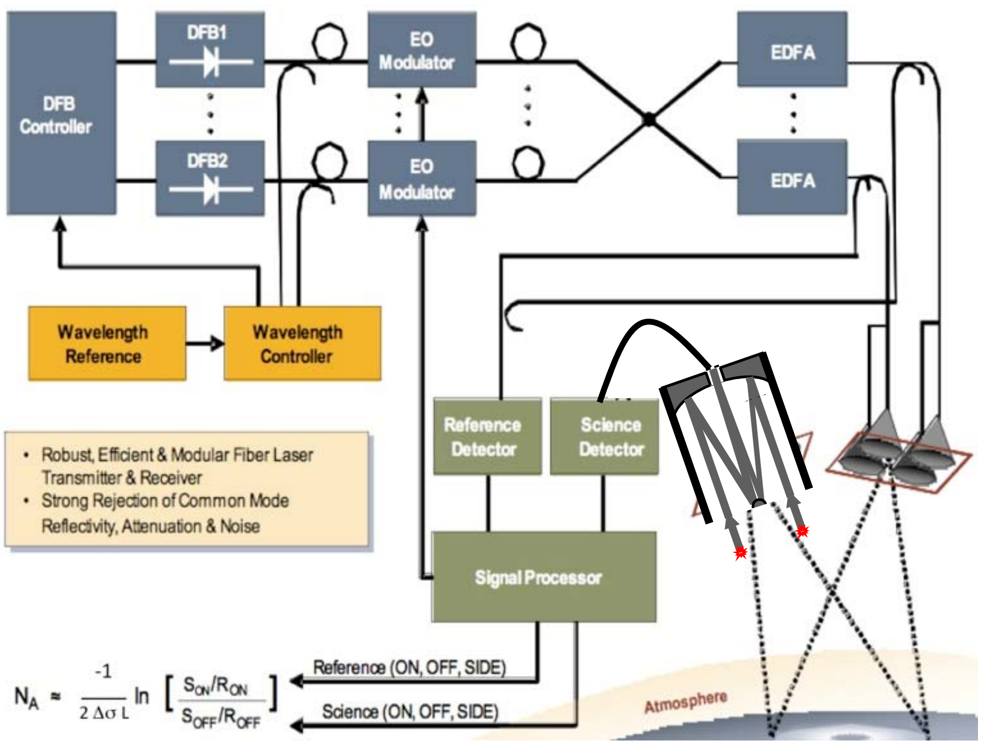
The **ASCENDS CarbonHawk Experiment Simulator (ACES)** is an Instrument Incubator Program (IIP) project that seeks to advance technologies critical to measuring atmospheric column carbon dioxide (CO_2) mixing ratios from space in support of the ASCENDS (Active Sensing of CO_2 Emissions over Nights, Days, and Seasons) Decadal Survey mission:

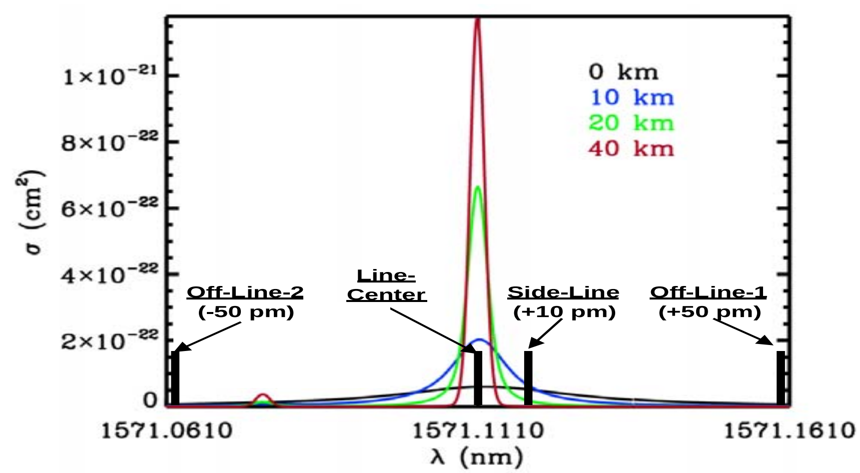
- Passive satellite measurements cannot make retrievals of CO_2 column densities to the surface at night, at high latitudes (i.e. northern Europe during winter and over the poles), and through cirrus clouds, high optical depth aerosols, or in presence of scattered clouds.
- Active measurements using lidars do not have these limitations, and they can therefore fill these data gaps and aid in the refinement and understanding of the global carbon cycle budget.

1.57-µm CO_2 Measurement Architecture

ACES architecture based on Exelis Multi-functional Fiber Laser Lidar (MFLL):

Dobler, et al., *Applied Optics*, 2013





– Simultaneously transmits multiple wavelengths (λ_{on} / λ_{off}) reducing atmospheric noise & eliminating surface reflectance variations.

– Approach is independent of the system wavelength and allows simultaneous CO_2 & O_2 (1.26 µm) measurements for deriving mixing ratio (XCO_2).

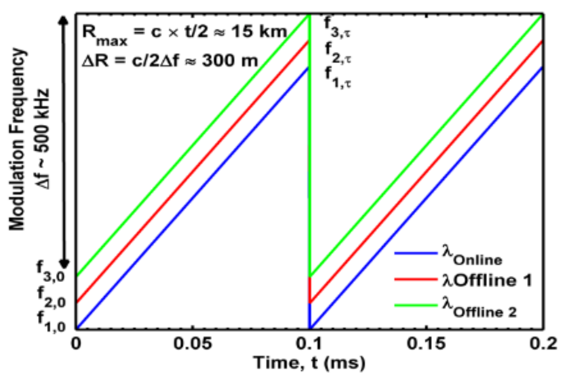
Intensity-Modulated Continuous-Wave (IM-CW) Measurement Technique

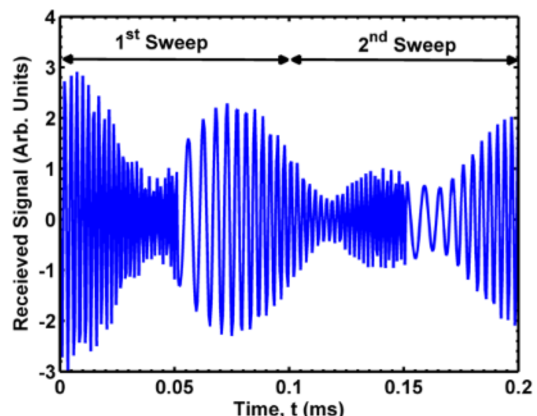
Progression of Transmitted and Received Intensity-Modulated Waveforms

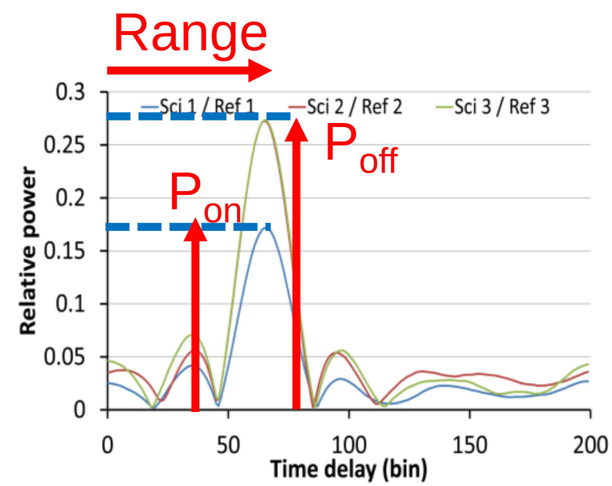
Simultaneously-transmitted intensity modulated range encoded waveforms

Simultaneously-received Online and Offline IPDA returns

Measurement: Output of correlation between transmitted and received waveforms







Range-encoded approach for detection and ranging is analogous to mature Frequency-Modulated Continuous Wave (FM-CW) Radar and GPS measurement techniques

$$DAOD = \frac{1}{2} ln\left(\frac{P_{off} * E_{on}}{P_{on} * E_{off}}\right)$$

Technology Challenges

ACES is advancing 4 key technology areas:

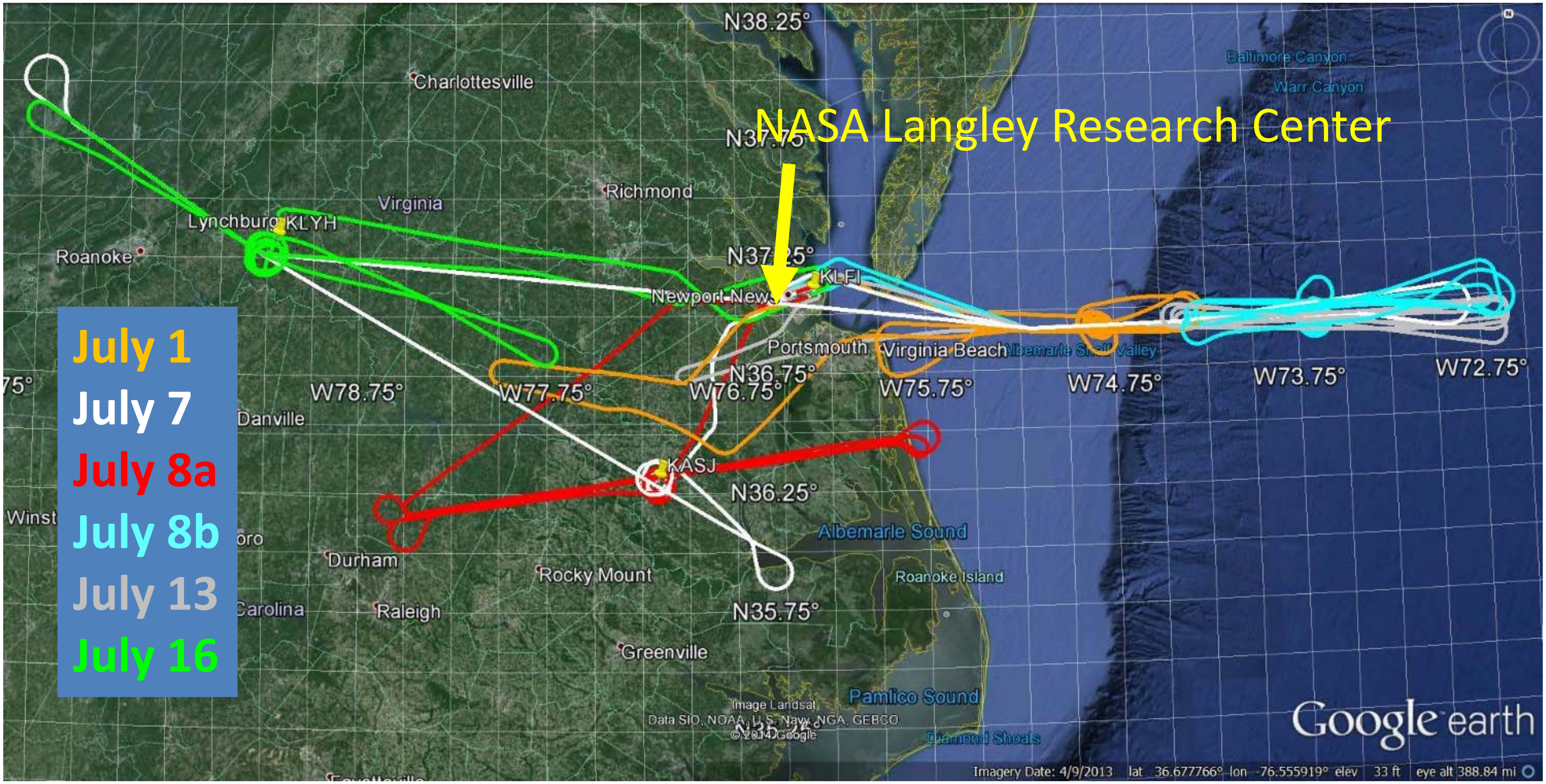
(1) Enable development of more advanced modulation waveforms with improved detector subsystem

(2) Increase transmit power and efficiency for CO_2 measurements at 1.57 microns using commercial amplifiers with stable, tunable laser-line locking system

(3) Demonstrate column CO_2 retrievals with alignment of multiple laser beams transmitting simultaneously in the far-field for scalability to space

(4) Continue refining CO_2 column retrieval algorithms in the presence of low optical depth clouds and distributed scattering layers (i.e. aerosol layers)

Flight Summary: 17.4 flight hours



Data recorded at multiple altitudes over land and ocean surfaces with and without intervening clouds.

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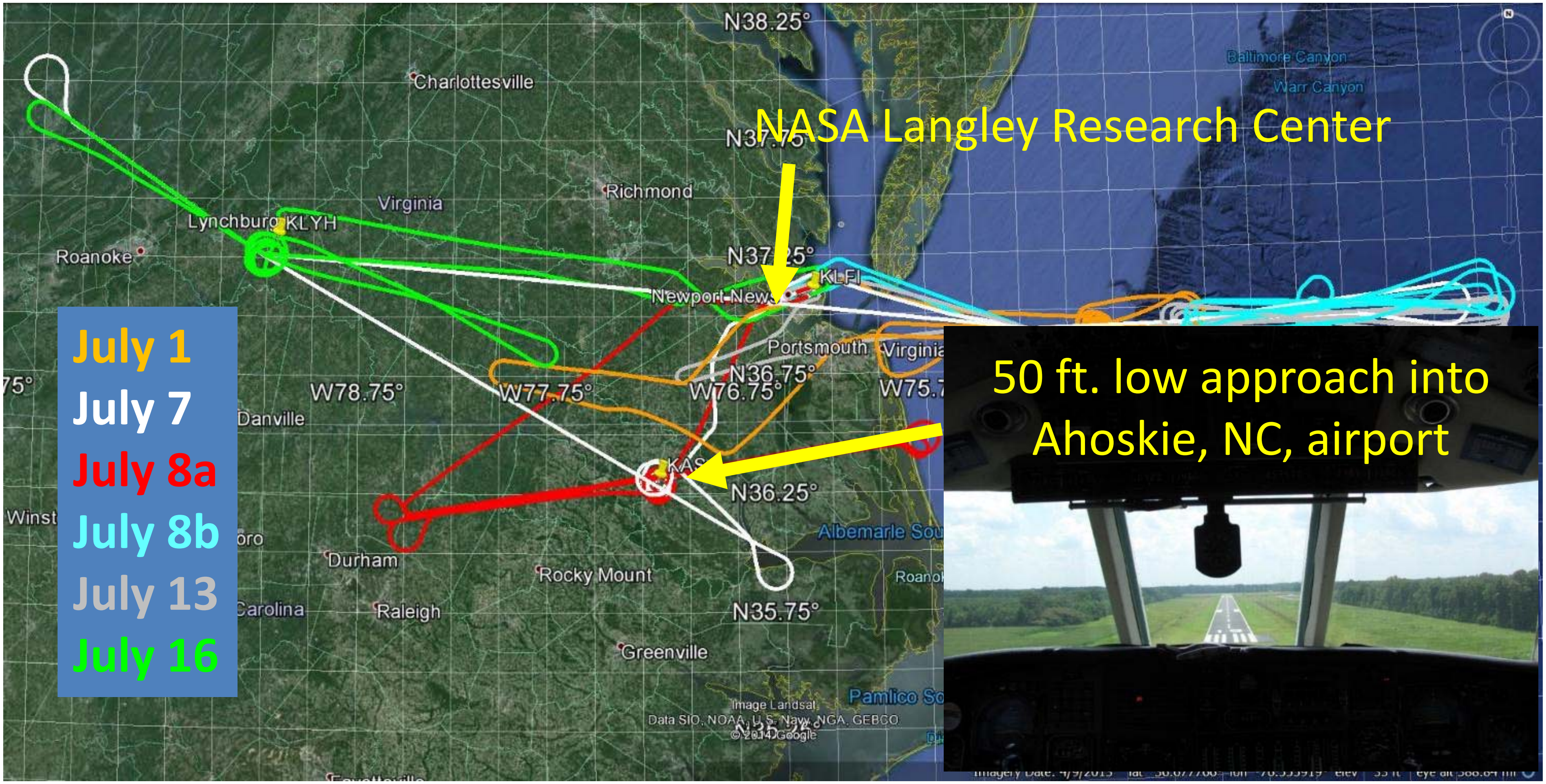

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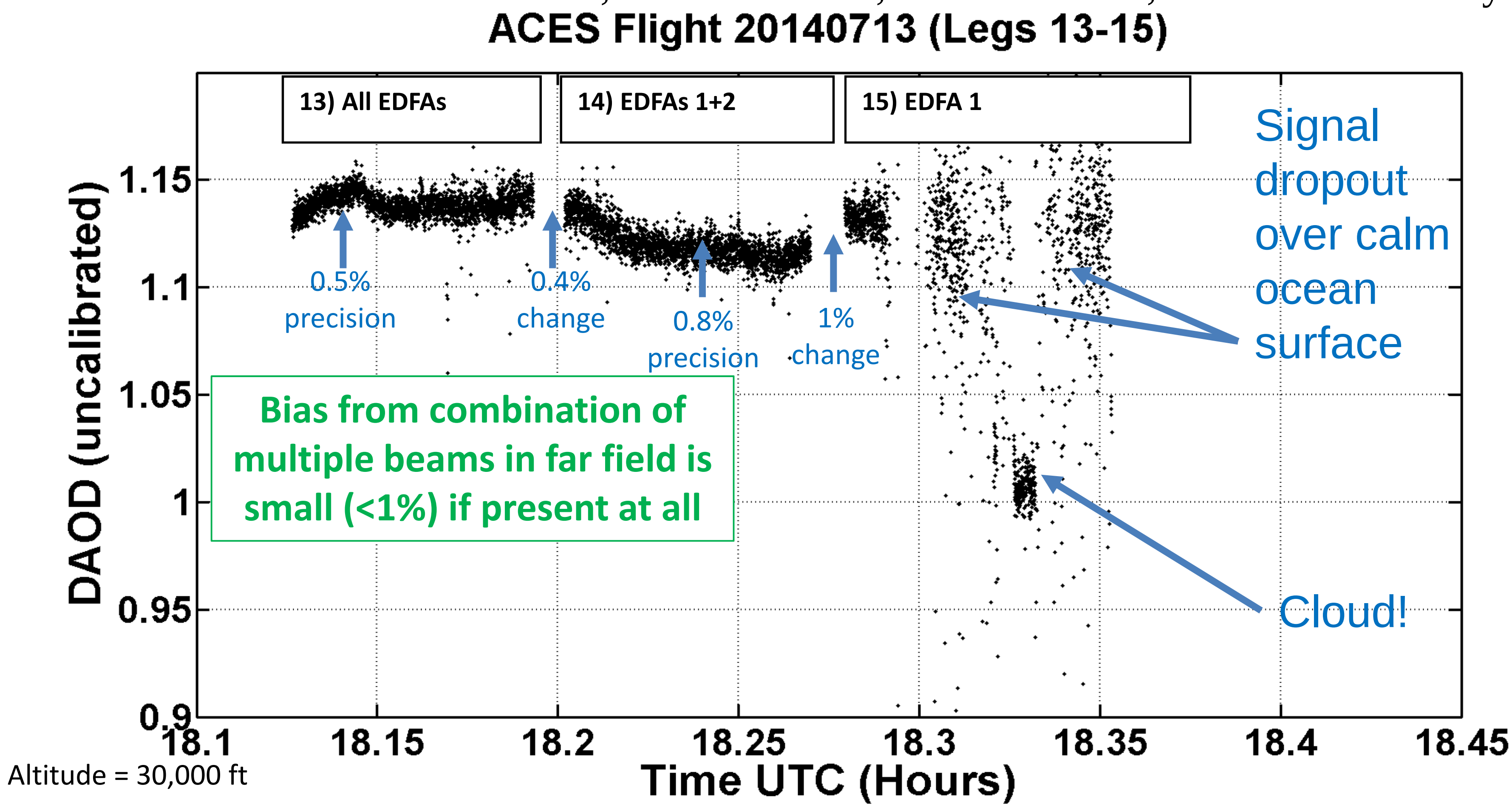
Preliminary Results: Combination of Multiple Transmitters

Major question for scalability to spaceflight is whether combining individual transmit beams in far field induces a bias in the measurements.

- Initial data show only small changes in measurements – about 1% on average – which could be due to beam combination bias, calibration drift, aircraft attitude, or natural variability.



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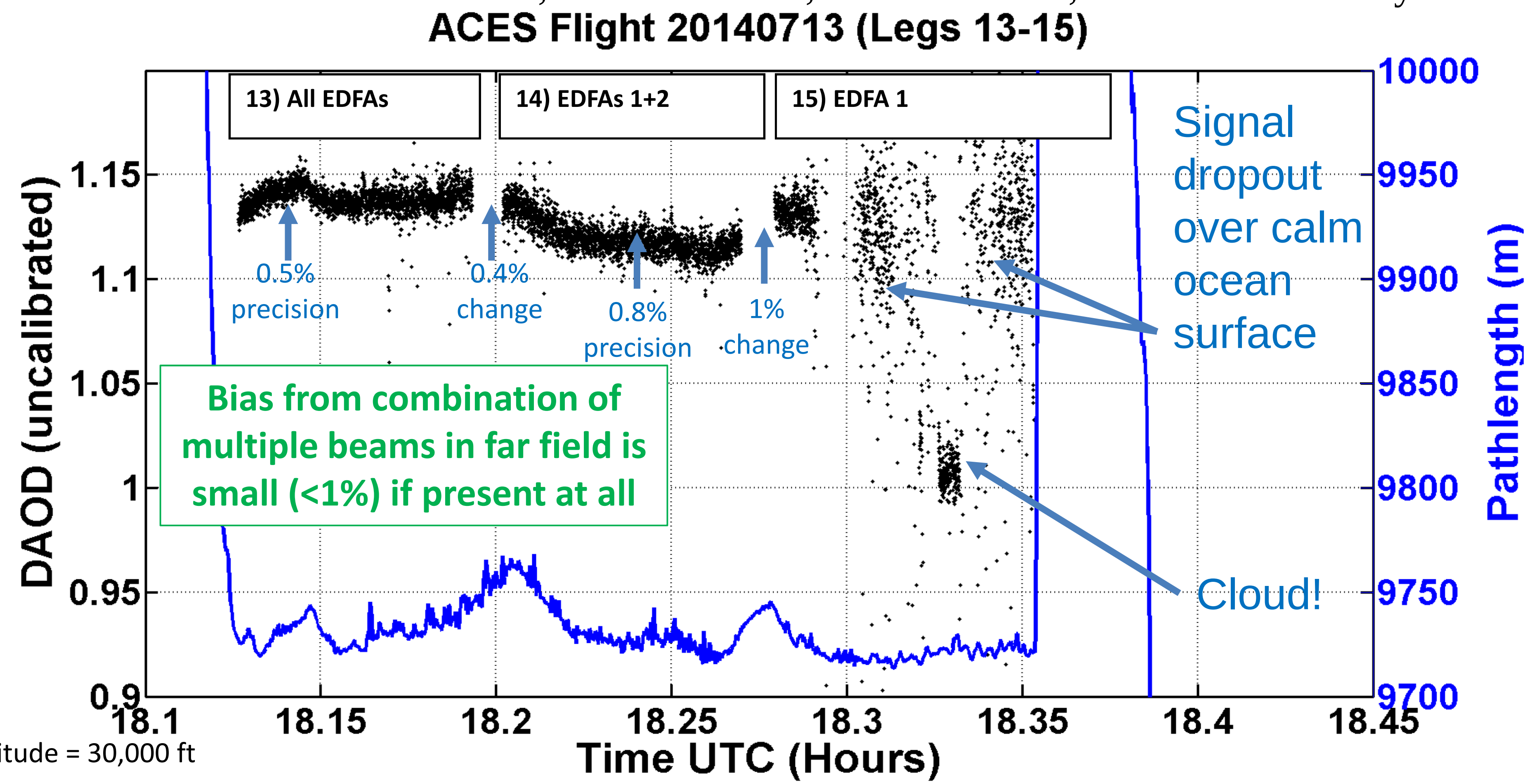
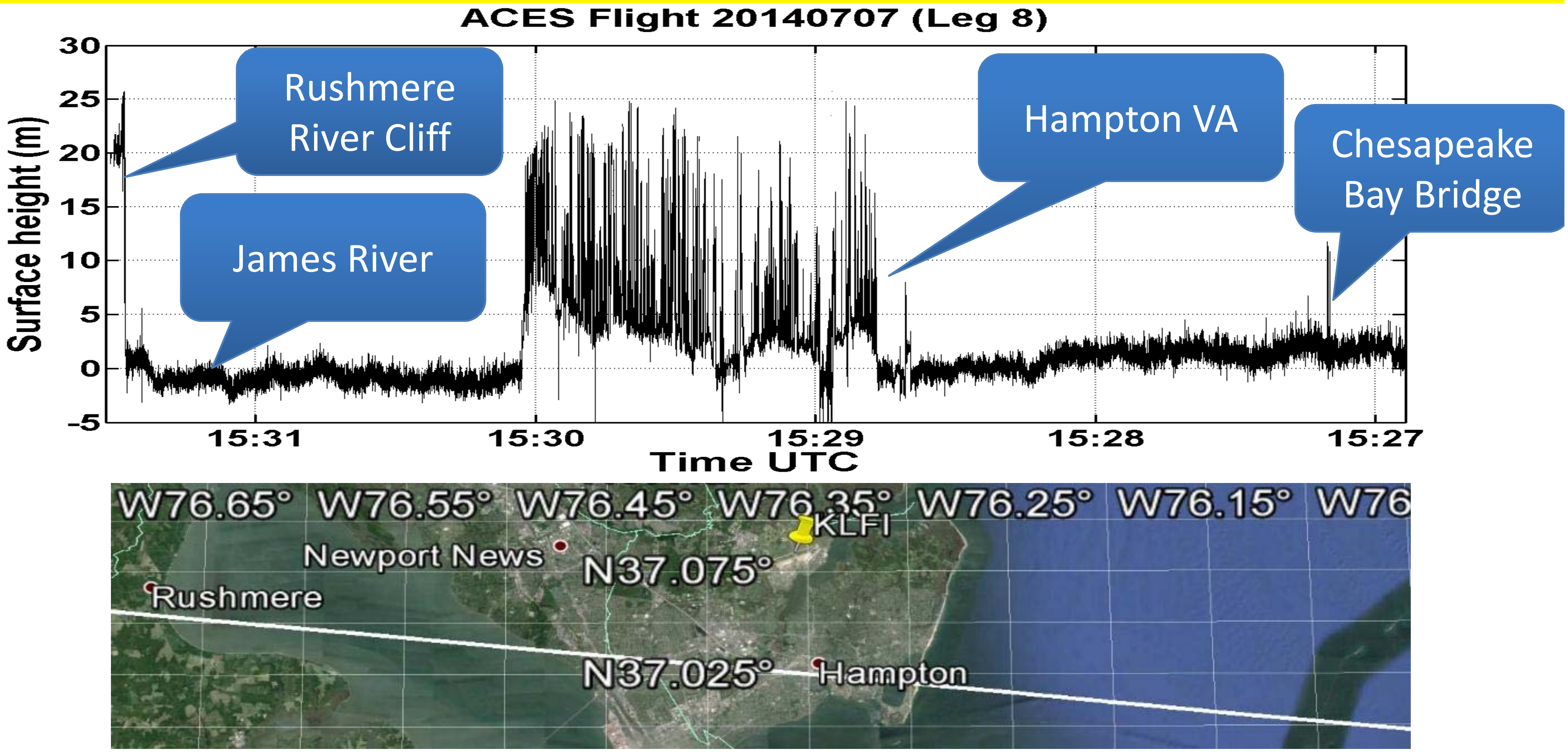


Altitude = 30,000 ft

Preliminary Results: Ranging



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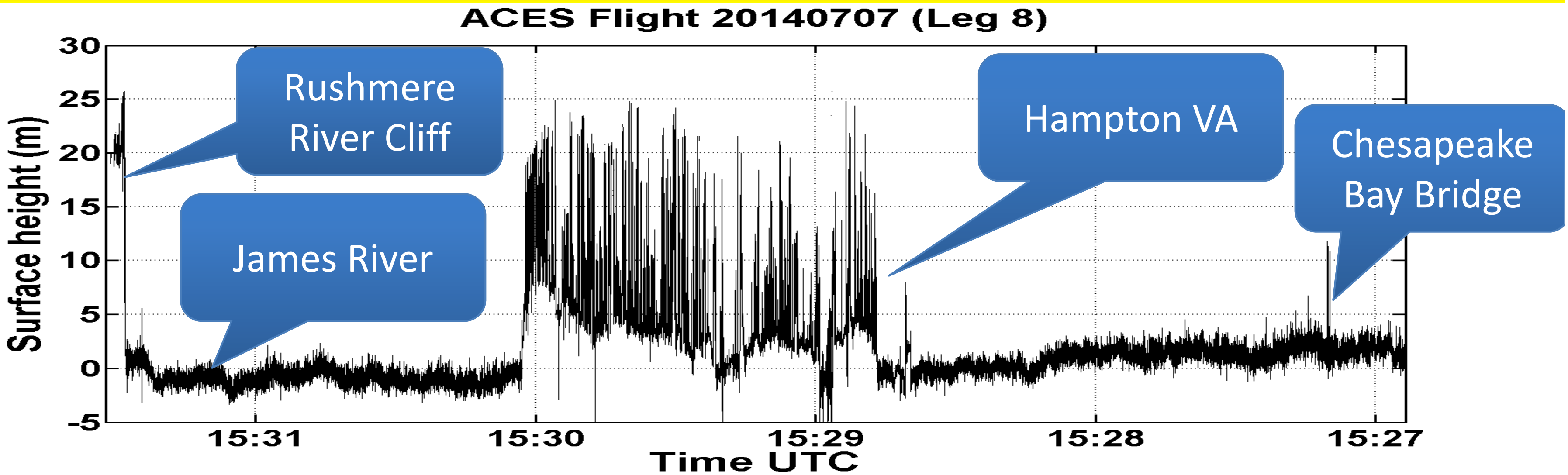

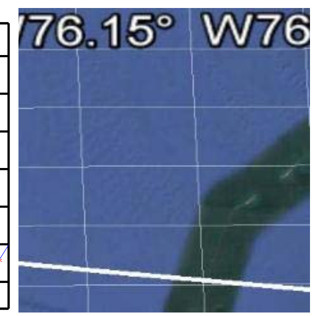

IM-CW technique accurately retrieves range over a variety of surfaces and in the presence of optically thin clouds allowing for retrievals of column CO2 mixing ratios to surface and cloud tops.

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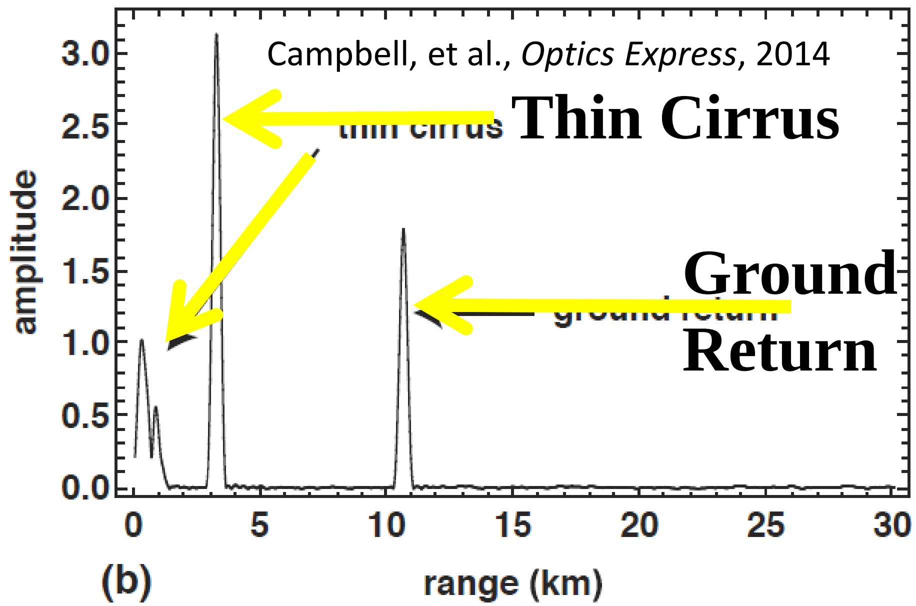
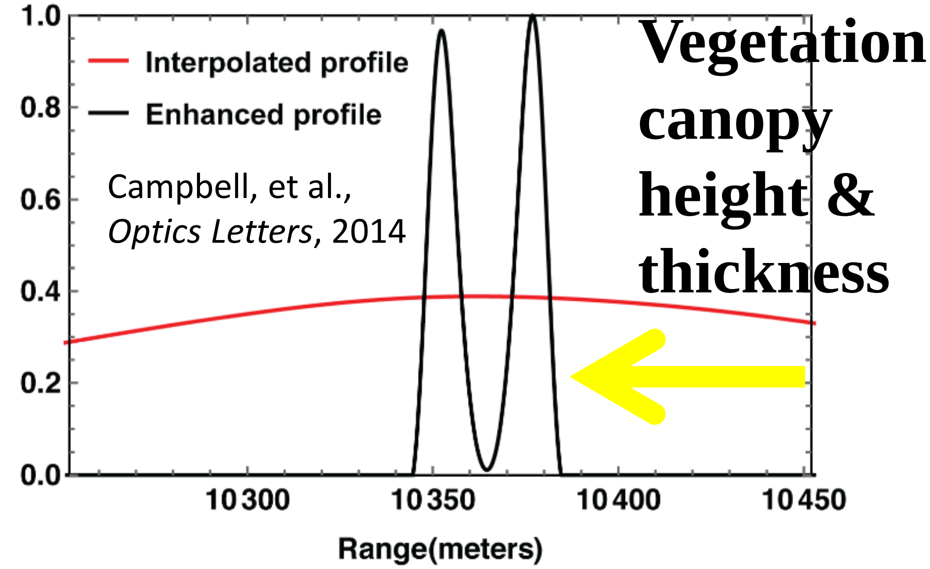
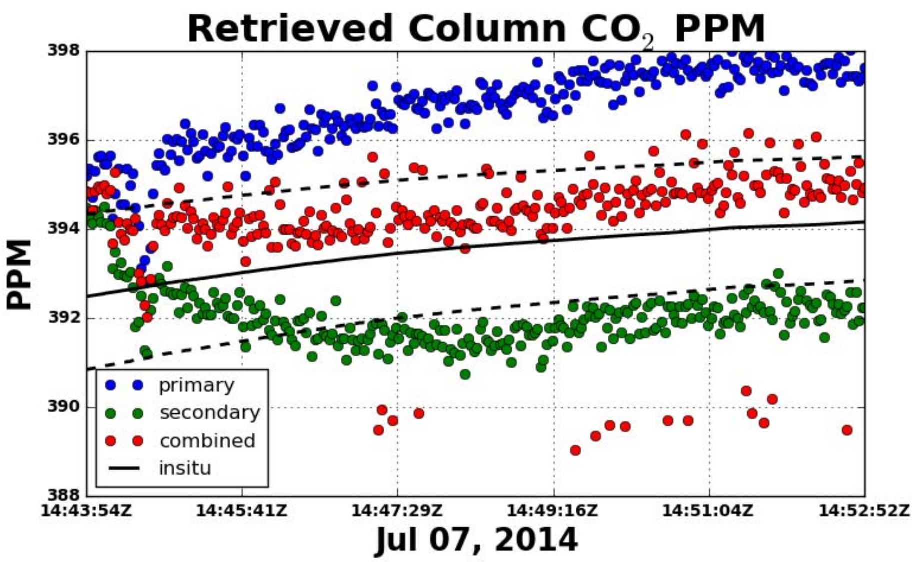
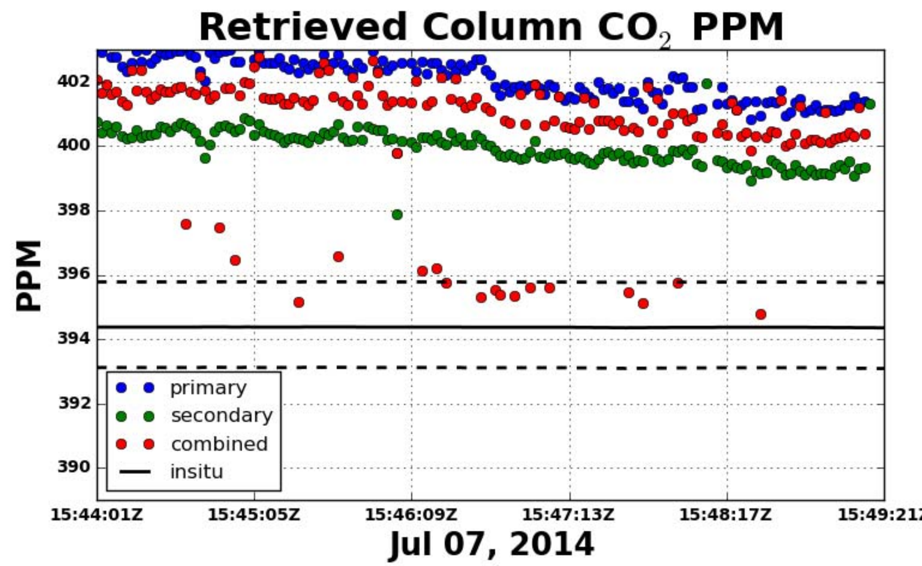


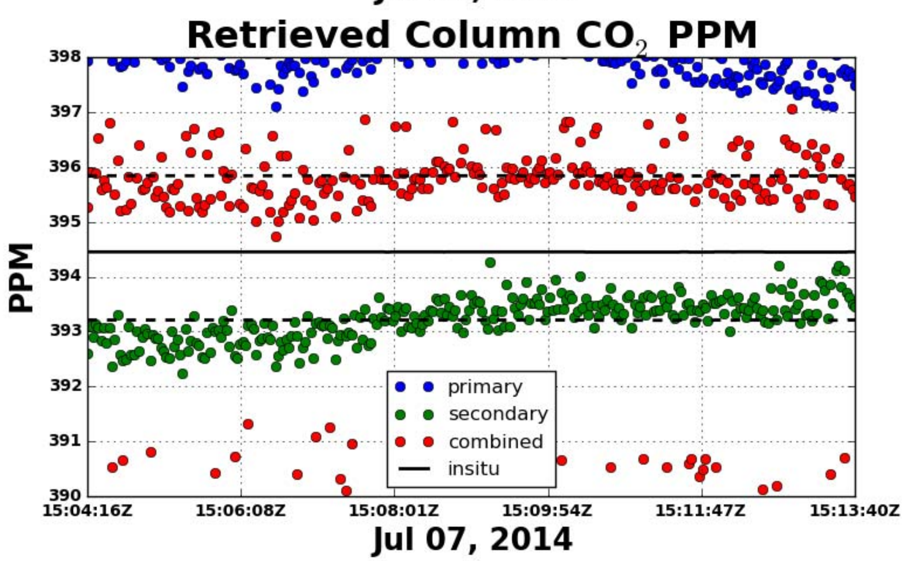


- Advanced deconvolution techniques resolve cloud and forest features:
  - Fourier transform reordering (**Interpolated** profile)
  - Richardson-Lucy deconvolution (**Enhanced** profile)

Preliminary CO_2 Retrievals: Ocean and Land







- CO_2 retrieval values (2-s average) are calibrated using primary and secondary offline wavelengths
- Average of in situ data across entire flight (binned by altitude) used for comparisons
- Actual CO_2 number densities likely different far away from spiral point and airport
- Further work is needed to compare directly with data from in situ spirals

Summary

- The ACES team is advancing technologies critical to making CO_2 column mixing ratio measurements from space.
  - HgCdTe detector/TIA bandwidth increased to ~4.9 MHz for advanced modulation waveforms
  - Increased transmitter power and receiver aperture yielding high precision measurements over varying surfaces
- ACES recorded meaningful data at multiple altitudes over land and ocean surfaces, with and without intervening clouds during its first test flights.
  - Preliminary data show excellent range retrievals that can produce cloud and vegetation canopy structures using advanced deconvolution techniques
  - Initial CO_2 retrievals show reasonable agreement (~1 ppm) compared with in situ measurements over water; over land measurements need more study
- Data analysis, comparisons, and technology advancement efforts are continuing.

Future Directions

- Continue data analysis to fully quantify instrument performance
- Continue flight testing of new modulation algorithms and hardware improvements
  - Deconvolution techniques for clouds and forest canopies
  - Operational tests of retrievals with sideline wavelengths
  - Instrument automation for UAV operations
- Continue Technology Readiness Level (TRL) advancement and space qualification of ASCENDS technologies
  - Example: Small Business Innovation Research project with Fibertek for laser amplifier advancement

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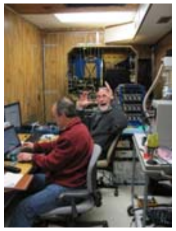
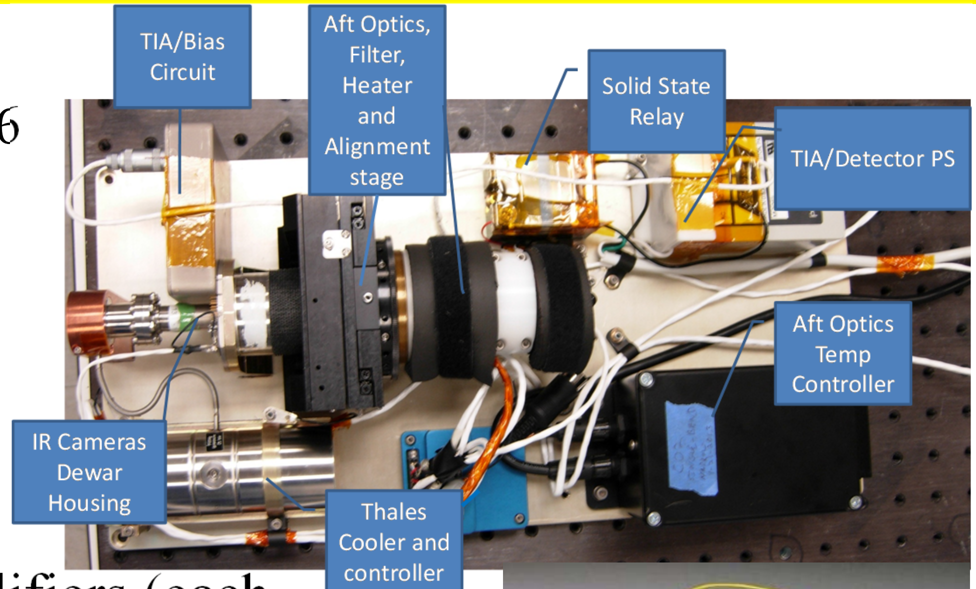


Backup Slides

Transmitters and Telescopes

DRS Technologies HgCdTe array

- ~4.9 MHz bandwidth @ gain of 10^6
- Continuously cooled at 77 K
- NEP: 2.4 fW/Hz$^{1/2}$
- Excess Noise Factor: ~1.1
- Tested with MFLL on DC-8 in 2013



Transmitters:

- Three Erbium-Doped Fiber Amplifiers (each 10 W average, 20 W peak) locked to CO_2 absorption line (1.57 microns)
- Wavelength tunable within +/- 50 pm (6 GHz) from line center

Combination of low-noise detector, higher power transmitters, and larger collection apertures improves signal-to-noise ratio; increased bandwidth allows for use of more advanced modulation waveforms.

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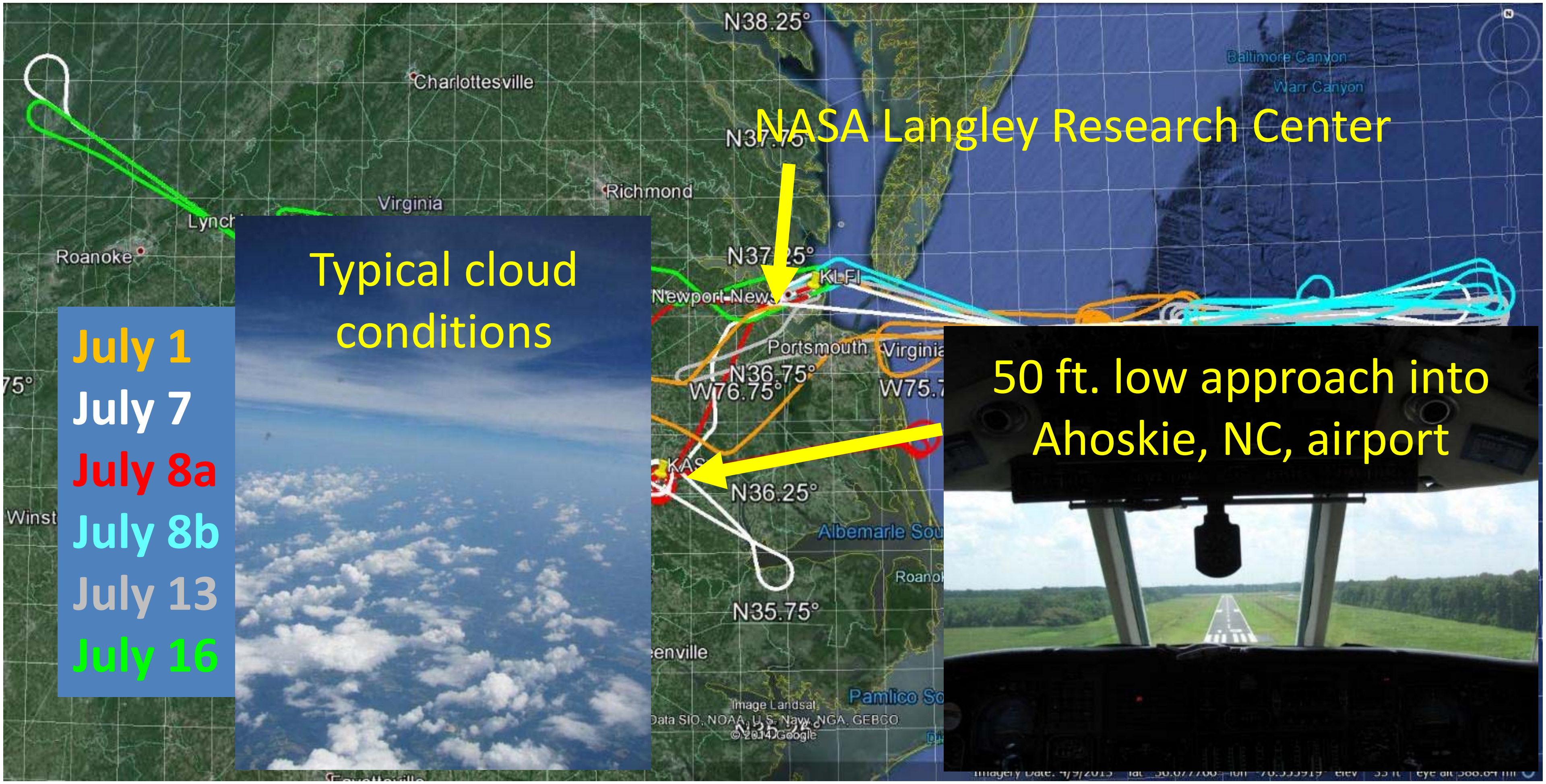

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